PART V: Accelerators for industrial applications

Defining Industrial Applications of Accelerators?

- Generally, high energy particle beams induce nuclear reactions and activation
- In contrast, in industrial applications, nuclear reactions and activation are undesirable and avoided, but other effects of ionizing radiations are searched for
- These desired effects include:
  - Sterilization
  - Cross linking of polymers
  - Curing of composite materials
  - Modification of crystals
  - Improvement of semi conductors
  - Beam aided chemical reactions

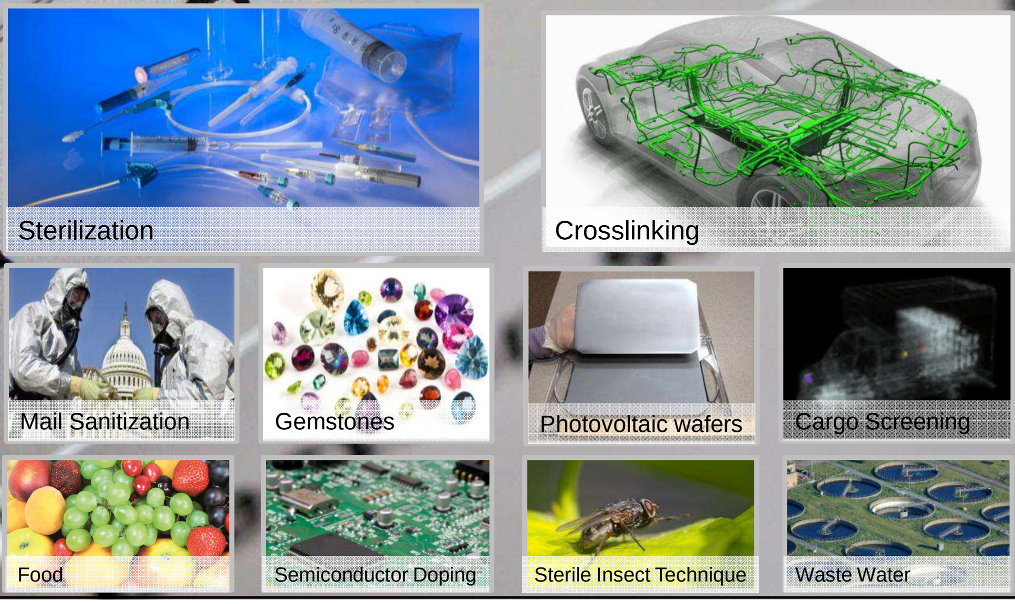
What beams are used?

- The choice of particle beams used in industrial applications is defined, to a large extent, by the desire to avoid nuclear reactions and activation.
- Commonly used beams include:
  - Electron beams below 10MeV.
  - X-Rays from e-beams below 7.5MeV.
  - Intense, low energy proton beams.
  - Low energy heavy ion beams (well below the Coulomb barrier).
- Also, for industrial applications, large beam currents/powers are needed to reach industrial scale production rates. Beam powers from 50 kW to 1 MW are common.

Key E-beam and X-ray Industrial Applications

- **Sterilization**
  - Sterilization of Medical Devices
  - Surface Sterilization
  - Food Pasteurization
- **E-beam induced chemistry**
  - Cross linking of Polymers
  - Curing of composites
  - Environment remediation
- **E-Beam induced crystal defects**
  - Improvement of Semiconductors
  - Coloring of Gemstones
- **Cargo screening**

INDUSTRIAL APPLICATIONS



IBA Industrial's Product Portfolio

Dynamitron
0.5 -> 5 MeV | 160 mA
Electron beam

Main application
E-beam Crosslinking

Rhodotron
3 -> 10 MeV | 42 mA | 420 kW
Electron beam and X-rays

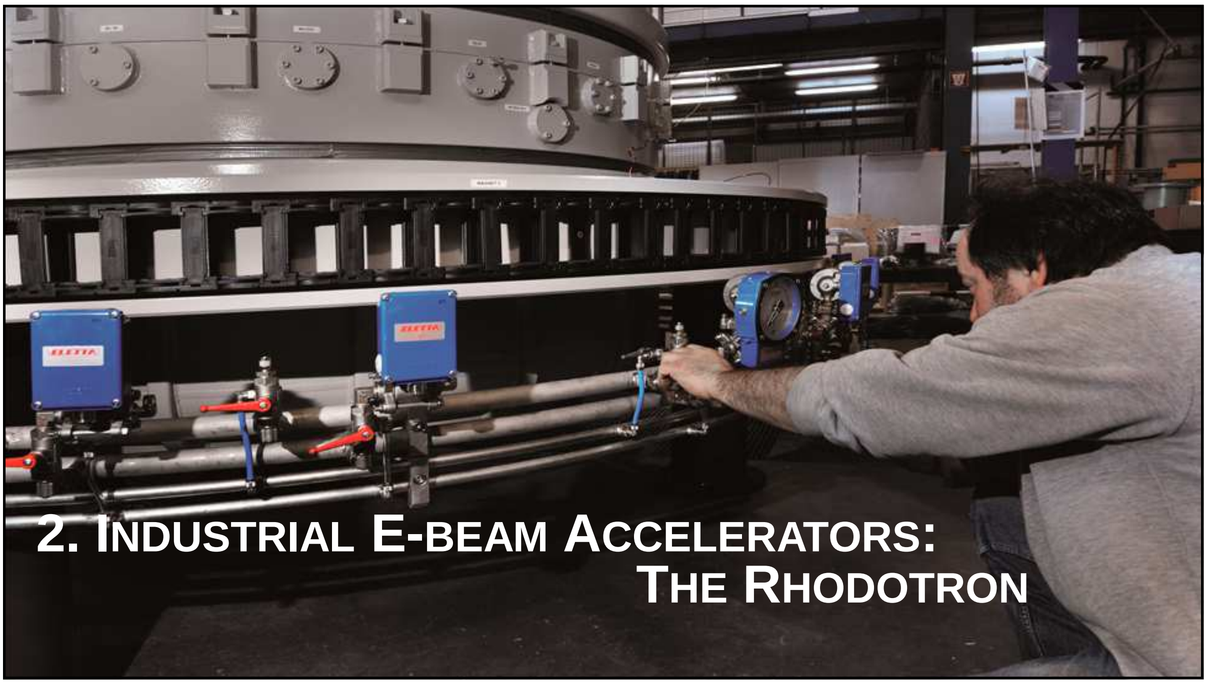
Main application
E-beam box sterilization

eXelis
5 – 7 MeV | 80 mA | 560kW
X-rays

Main application
X-ray pallet sterilization

Linac's reach about 40-60 kW

Protect, Enhance, and Save Lives



2. Industrial E-beam Accelerators: The Rhodotron

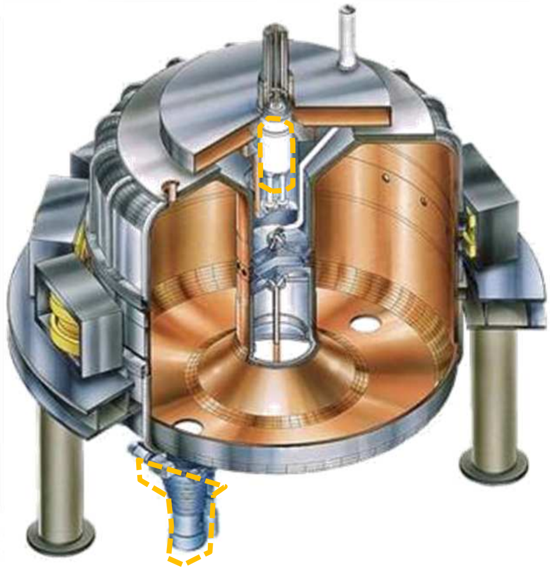
Brief explanation of the Rhodotron:

A short history

- 1989: First design by Pottier at French Atomic Energy Agency (CEA) → Patent for 20 yrs
- 1990: Prototype by CEA, at 3.5 MeV and 20 kW
- 1991: IBA/CEA collaboration gave IBA exclusive rights to industrialize the Rhodotron
- 1991-1994: First industrial unit designed: 5 & 10 MeV with CW power up to 100 kW
- 1995: First sale of a Rhodotron (Studer)
- 2012: First X-Ray TT 1000 in operation (Studer too) !
- 2015: Different models available (TT100-200/300-1000)

Brief explanation of the Rhodotron:

The main components

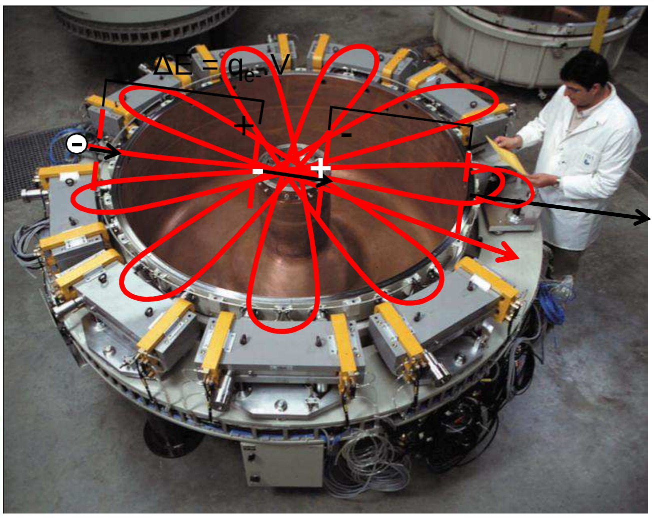


RF Cavity
E-Gun
Magnets
Final Power Amplifier

RF tube (Tetrode)
Vacuum system

Brief explanation of the Rhodotron:

Basic acceleration and re-circulation



Electrons are generated by the e-gun, then accelerated by the electric field in the cavity:

$$\Delta E_c = F.x = q.E.x = q.\frac{V}{x}.x$$

After the first acceleration pass, the electron path is curved by a magnetic field:

$$F = q.(E + v.B) = \frac{m.v2}{r} \Rightarrow B.r = \frac{m}{q}.v$$

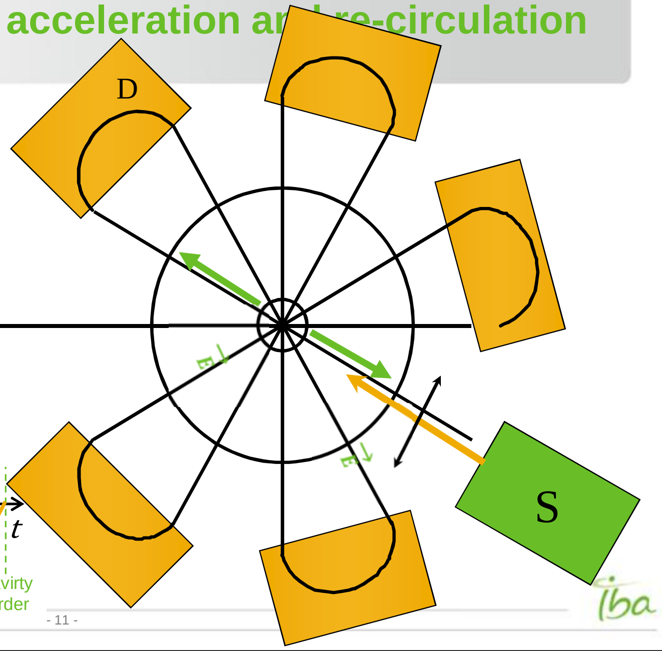
Important: electrons are relativistic after first pass: v = constant !

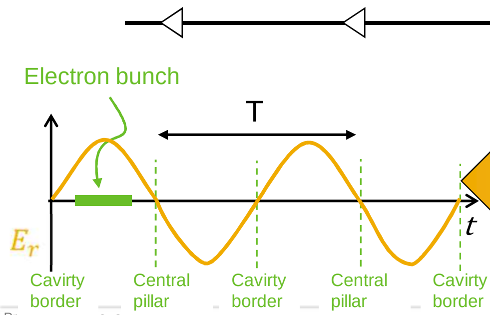
E (e-)	50keV	1MeV	10MeV
β	0.41	0.94	0.99
γ	1.098	2.956	20.56

The Rhodotron: Basic acceleration and re-circulation

time in [0,T/4]

- Electric field outward facing
- Electrons injected and travel first half crossing

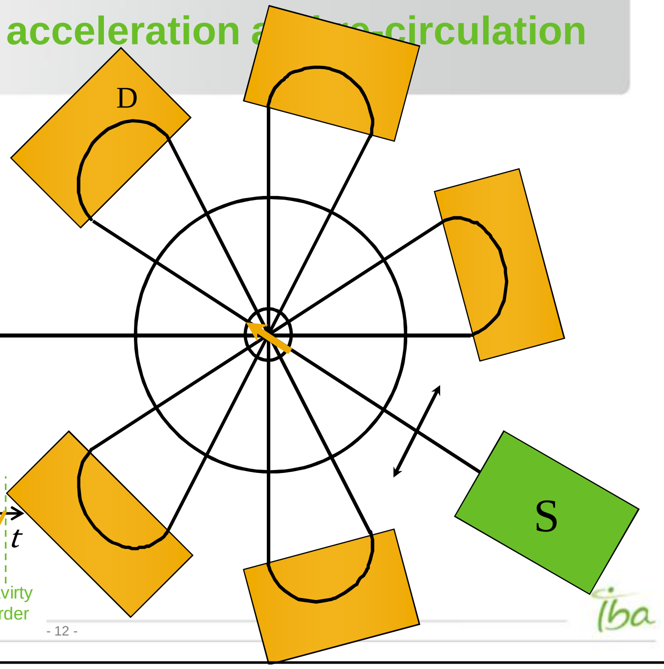


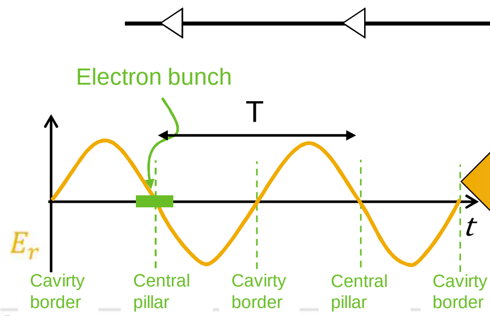


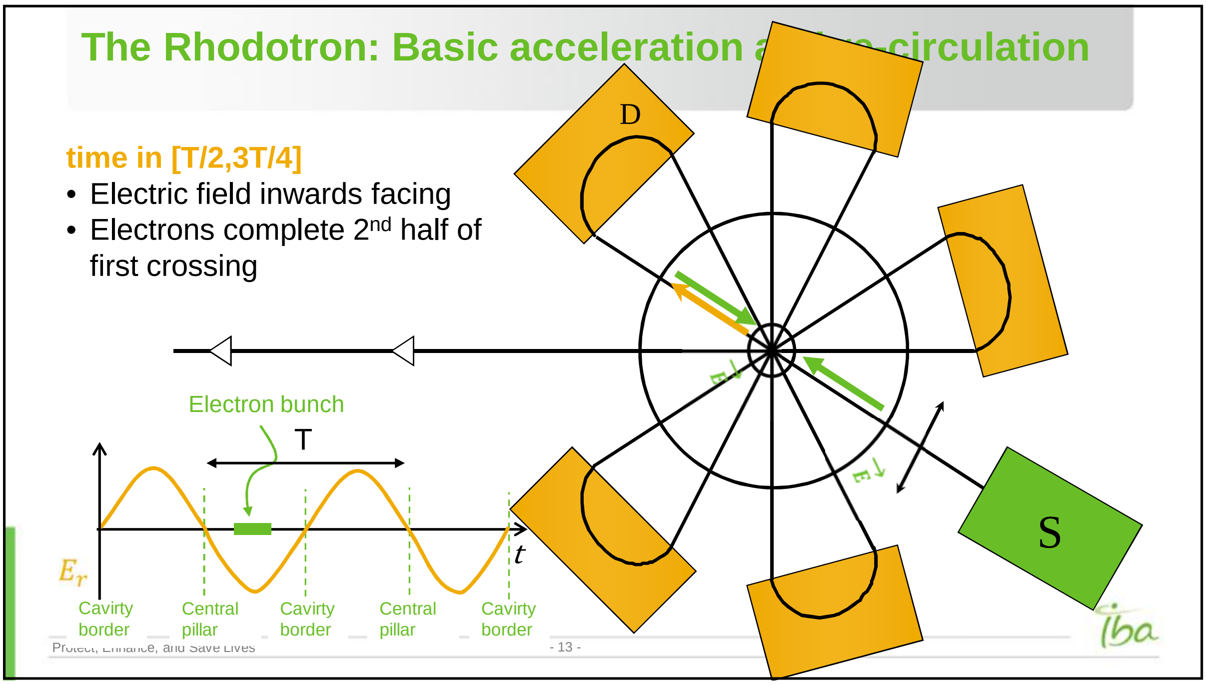
The Rhodotron: Basic acceleration and re-circulation

time in [T/4,T/2]

- Electrons cross inner cylinder holes (pillar)
- Electric field polarity reversing






The Rhodotron: Basic acceleration a
e-circulation
time in [T/2,3T/4]
• Electric field inwards facing
• Electrons complete 2nd half of first crossing
D
S
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E
Electron bunch
T
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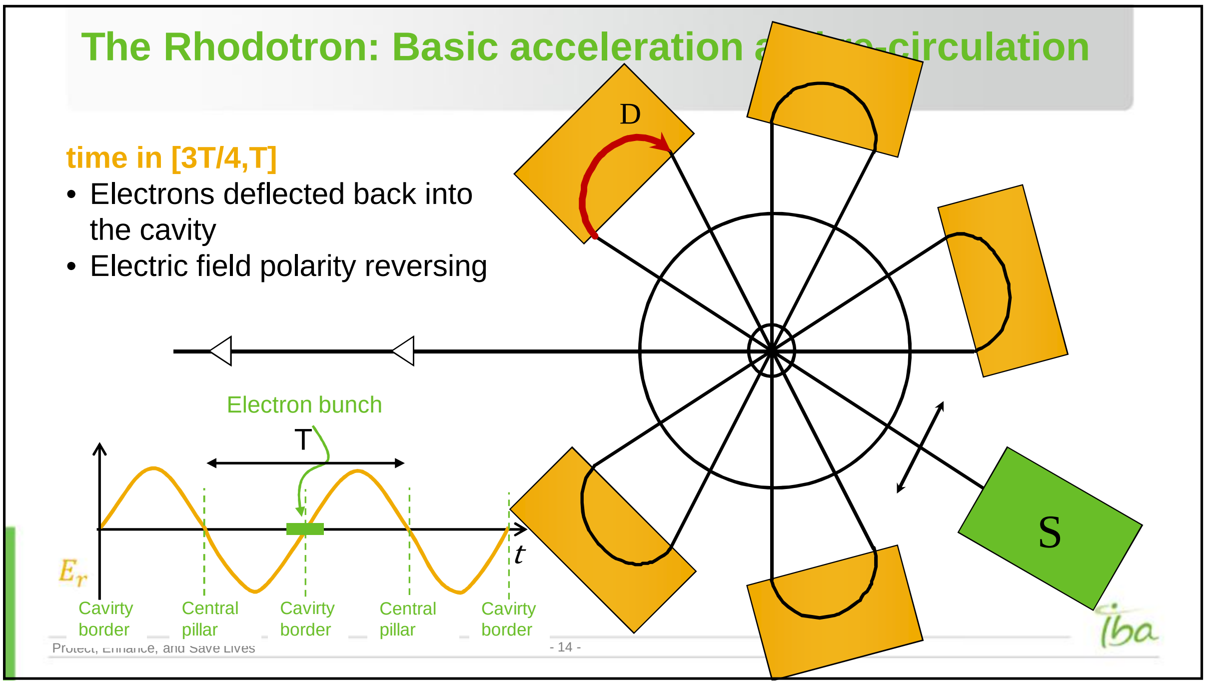
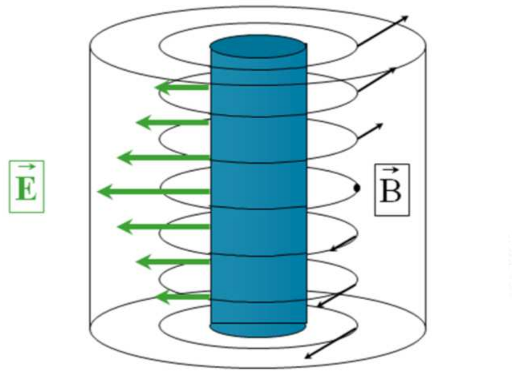
t
Cavity border
Central pillar
Cavity border
Central pillar
Cavity border
- 13 -
iba


The Rhodotron: Basic acceleration a
e-circulation
time in [3T/4,T]
• Electrons deflected back into the cavity
• Electric field polarity reversing
D
S
Electron bunch
T
E_r
t
Cavity border
Central pillar
Cavity border
Central pillar
Cavity border
- 14 -
iba

The Rhodotron: Cavity Design

Introduction to Rhodotrons e-beam accelerators



Electric (E) and magnetic (B) fields in Rhodotron coaxial cavity

① RF sinusoidal electrical field ➔ coaxial cavity !

② Frequency is 107 MHz (215 MHz for TT100). Depends on tube availability ➔ best is FM band

- The size of the cavity is fixed by f:
  - Height = 0.5 λ
  - Radius ideal is 0.35 λ to allow transit in magnets
- Fundamental mode (TEM 1):
  - Radial E-field and azimuthal B-field
  - E-field varies as cos (z) / r
- Electrical losses increase with $f^{1/2}$
- Cost increase with size, small is complicated for beam optics: phase acceptance & transmission

↳ **Maximize energy gain vs losses & cost !**

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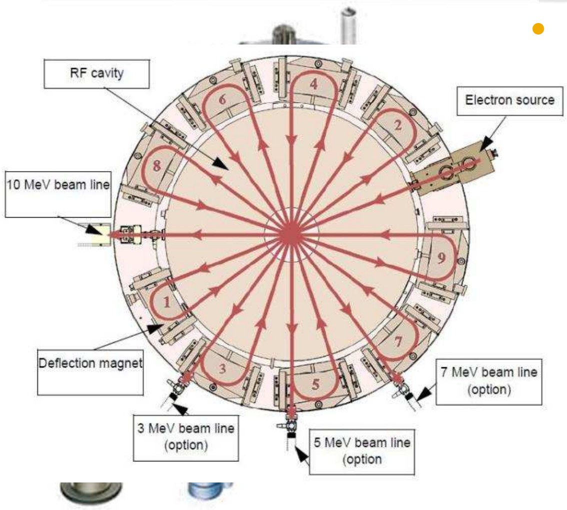
The Rhodotron: Cavity Design

Introduction to Rhodotrons e-beam accelerators



- **Interesting design notes:**
  - 70 kW to polarize the cavity, 5000 Amps in the walls
  - Electrical field is max in the median plane and Magnetic field is max at top and bottom → Easy magnetic coupling
  - Rounded cavity's bottom is to reduce RF power and shift secondary modes
  - Total flight of the electrons is *ca.* 28 meters
  - Beam can be extracted at each magnet
  - Cavity holes and space charge are critical
  - **First pass is the most critical because of beam low energy (50 keV to 1 MeV)!**

Protect, Enhance, and Save Lives - 16 -

Transverse focusing in the Rhodotron

- From the RF–fields
  - Electric => holes in the cavity walls
  - Magnetic => Perpendicular to the radially directed cavity passes
  - Note that the B and E-fields are 90° out of phase
- From the bend magnets
  - Pole face angles are chosen such as to provide weak horizontal and vertical focusing

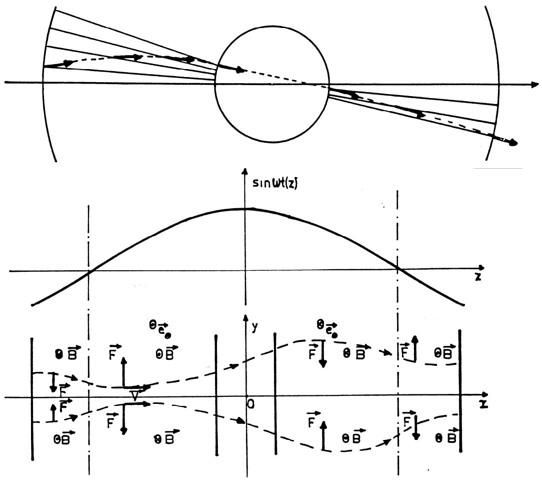
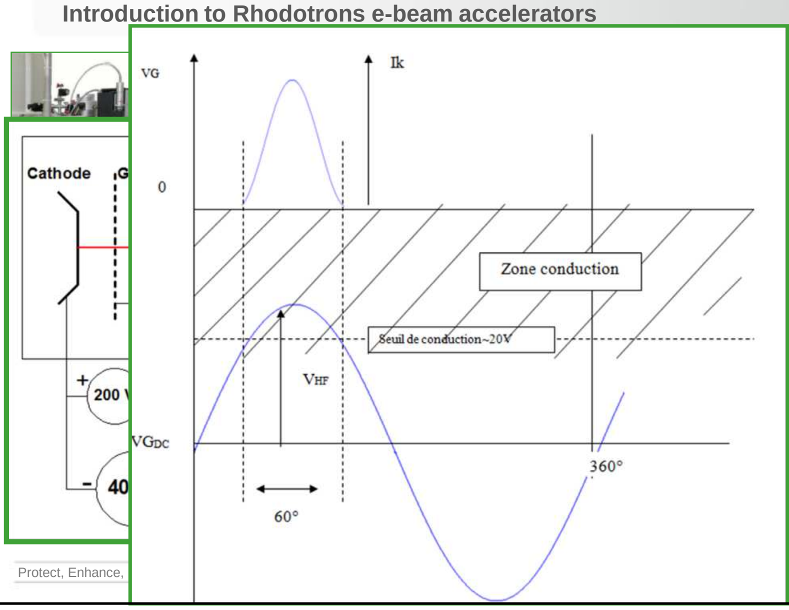


Figure 3.7 : Effet alternativement focalisant et défocalisant du champ magnétique.

The Rhodotron: E-gun

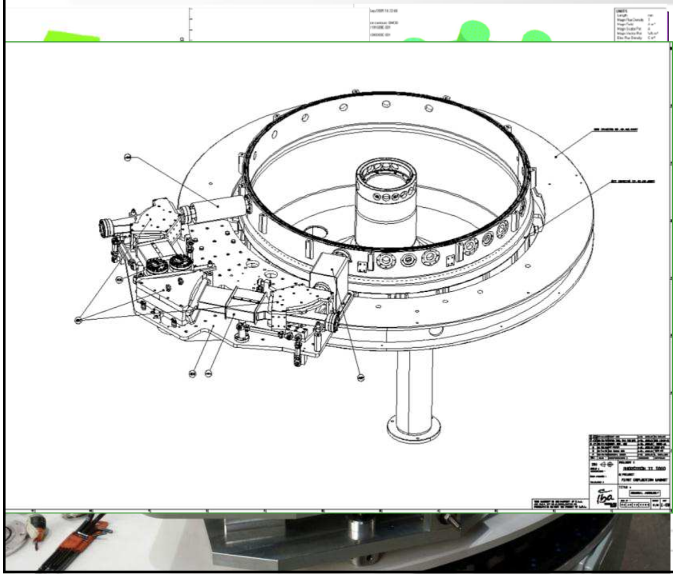
Introduction to Rhodotrons e-beam accelerators



- **E-Gun Design:**
  - Low work function heated flat cathode with modulation grid
  - Extraction at 40 kV
  - Neg. Bias grid
  - Driven by RF to avoid beam losses (pick up)
  - Capture during 1.5ns (60° of phase)
  - Peak current: 1A

The Rhodotron: deflection magnets

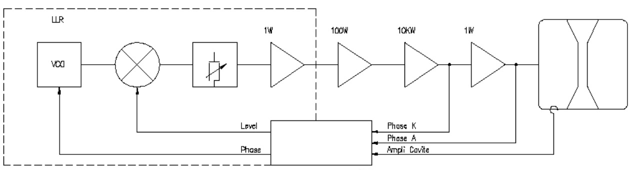
Introduction to Rhodotrons e-beam accelerators



- **Magnet Design:**
  - Simple dipoles with adjusted pole face angles
  - Fringe field has a strong impact on transmission
  - Magnets are different for TT100, TT200, TT300 and T1000 to increase max current
  - TT1000 has acromatic magnet 1 to increase max current to 100 mA: increase phase acceptance, control beam size and reduce fringe field

The Rhodotron: RF Chain & Final Power Amplifier

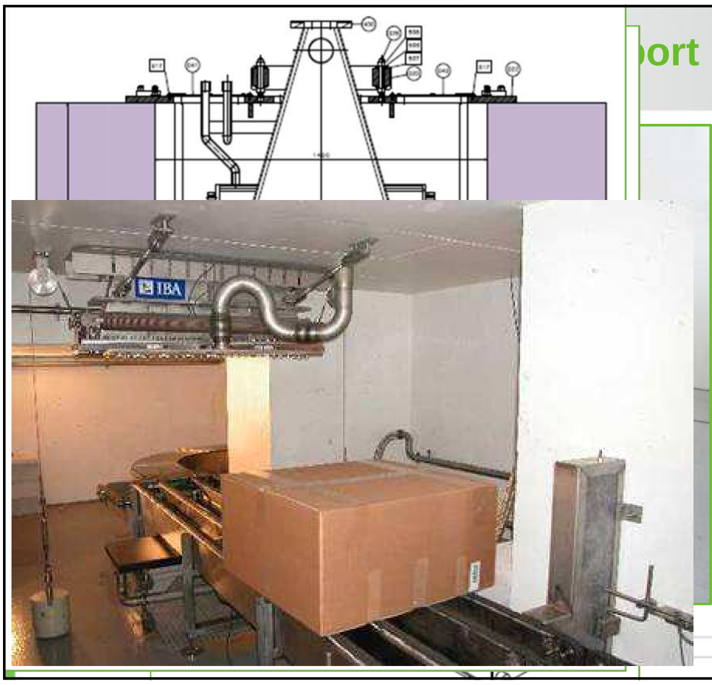
Introduction to Rhodotrons e-beam accelerators



- **How to polarize the cavity at 680kV and 107 MHz ?**
  - Cavity is a resonator (Q > 40000)
  - Signal is created in the Low Level Rack (LLRF) and transmitted to the cavity through RF chain
  - From 1W in LL-rack to 280kW in the cavity
  - Phase in controlled and adjusted
  - Power is coupled to cavity with a coupling loop in the coupler

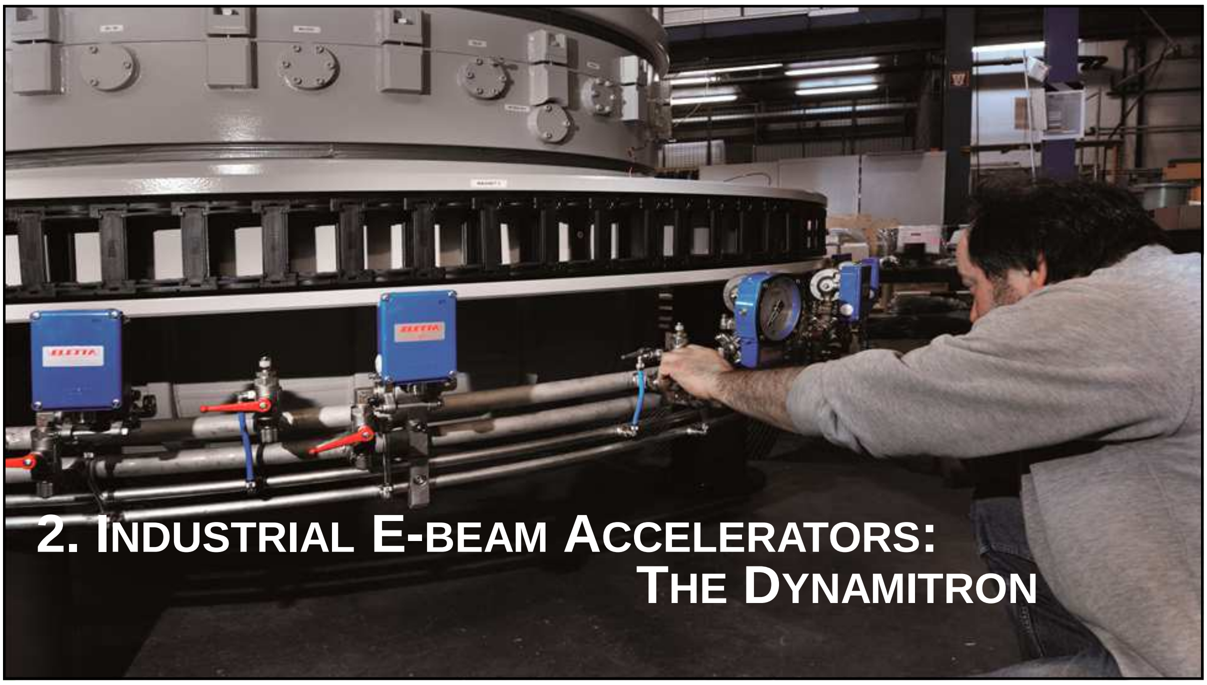
Protect, Enhance,

ort line, Scanning, Horn



Goal of the BTL and horn ?

- Transport beam from Rhodo vault to target without any losses
- Scan the beam across the material to be treated according to conveyor speed
- Convert electrons to X-ray when needed



2. Industrial E-beam Accelerators: The Dynamitron

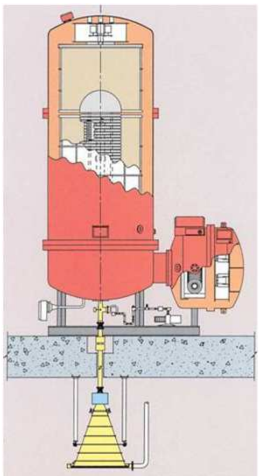
Dynamitron
Generalities

- Electron or proton beam, up to 160 mA of beam current
- Energy range : 500 keV to 5 MeV
- Applications - electron:
  - Cable insulation cross-linking
  - Sterilization (medical devices)
  - Improvement of the color of glass and gemstones
  - Electronic pasteurization
  - …
- Applications - proton:
  - Photovoltaic silicon wafer slicing
  - Cancer treatment by Boron Neutron Capture Therapy (project)
  - …





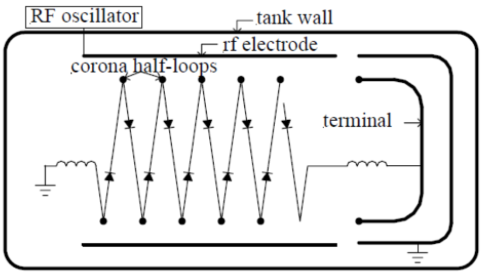
Dynamitron
High Voltage generation => similar to a Cockcroft-Walton

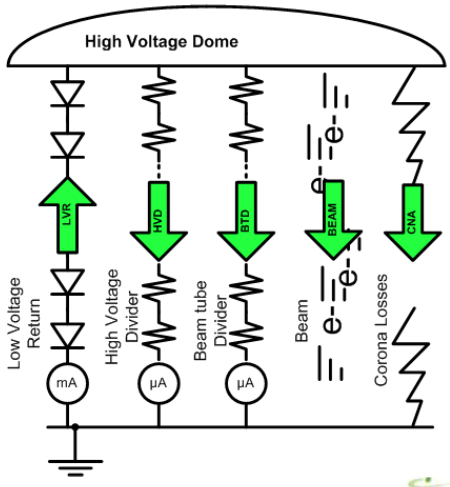



Dynamitron

Electron beam generation

- Parallel fed cascade voltage multiplier
- Accelerated from voltage drop from High Voltage (up to 5 MV DC) to ground.
- Beam in a long acceleration tube under ultra high vacuum (10e-8 mbar range)
- Beam = LVR – (BTD + HVD + CNA)

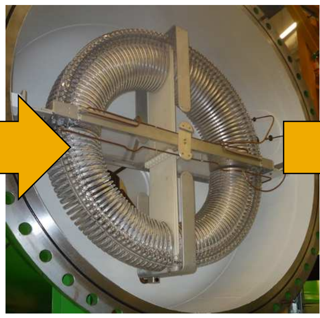




Dynamitron

Main components

Power oscillator



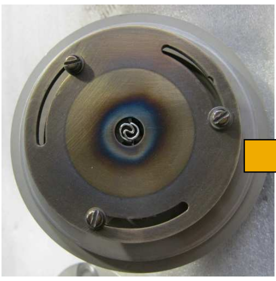
RF transformer

Dome

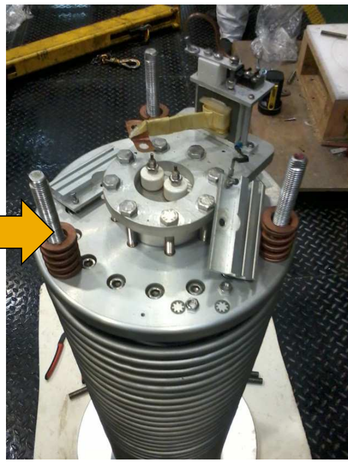
Dees and rectifier stack

Dynamitron

Main components



Electron gun



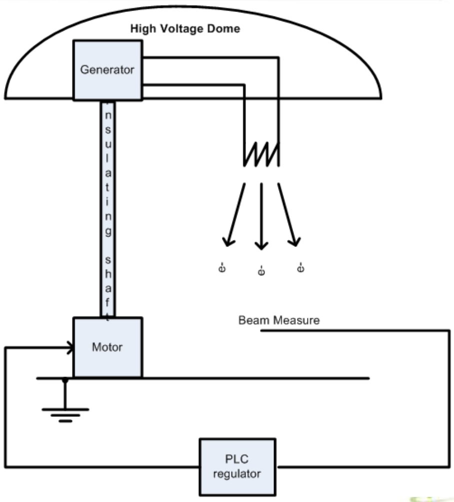
Beam tube

Scan Horn

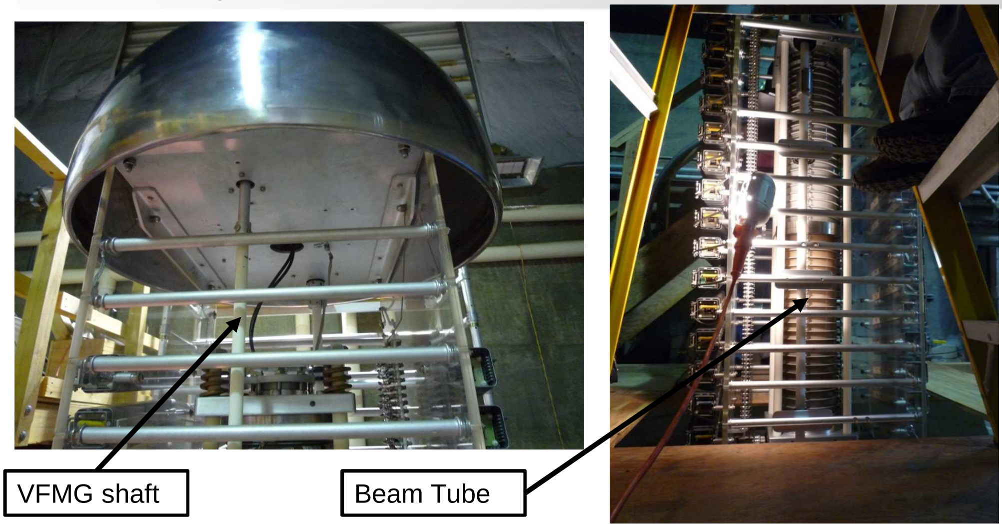
Dynamitron

Beam regulation – How to heat up the filament ?

- VFMG (Variable Frequency Motor Generator) to generate filament power at High Voltage terminal
- Filament heating voltage is generated by a variable frequency motor generator
  - Motor is at ground level
  - Insulated shaft to hold the high voltage
  - Generator in high voltage terminal



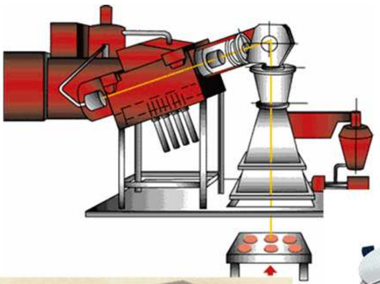
Dynamitron
Electron beam generation

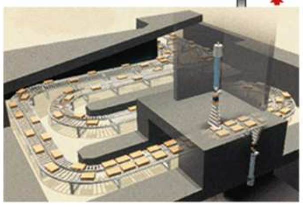


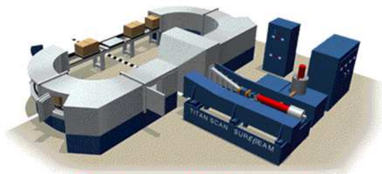
Some Dynamitrons…
Easy-E-Beam

- Self Shielded
- Compact
- Right angle
- 800 kV
- 100 mA

High power E-beam accelerators => the Linacs

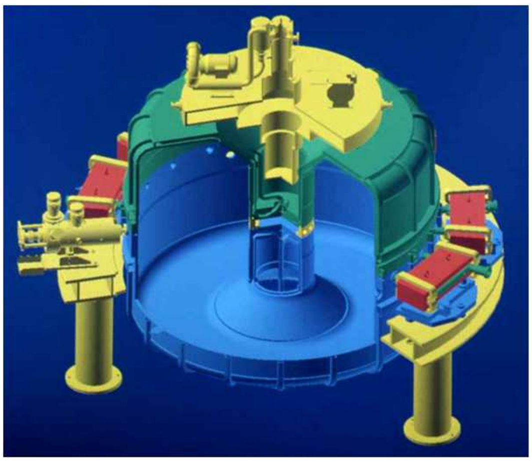






On-Site is a complete turn key operating system validated to ISO 11137 and delivered with all required training, documentation, dosimetry system and process certification.

High power E-beam accelerators: 1) the Rhodotron

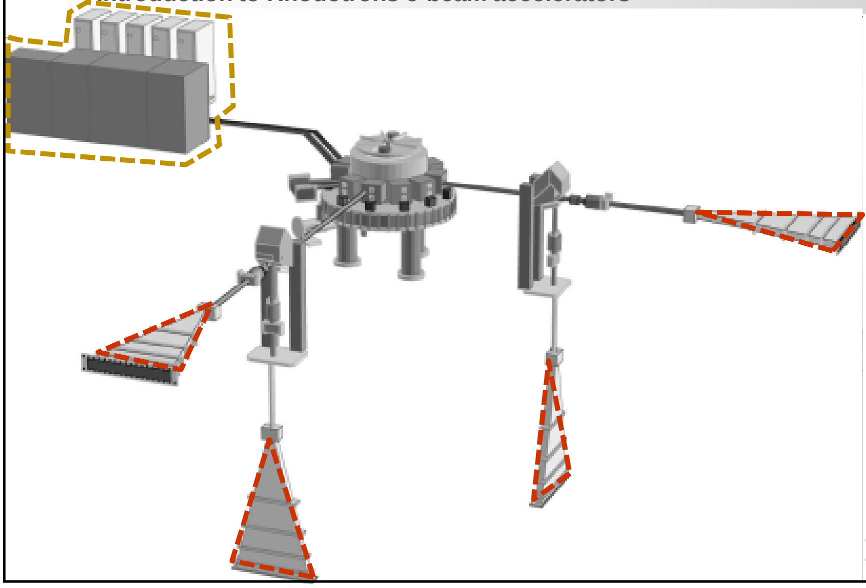


Typical applications:

- Modification of polymers
- Sterilization of medical devices
- Preservation of foods
- Treatment of waste materials
- Gemstones and semiconductors

The Rhodotron: Other sub-systems : Bill of Material

Introduction to Rhodotrons e-beam accelerators



RF Cavity
E-Gun
Magnets
Final Power Amplifier

Vacuum system
RF Tube (Tetrode)

Cooling & pneumatic system
Beam Transport line
Power Supply Room
Horns & Targets

Wrap up: The Rhodotron models & performance

Introduction to Rhodotrons e-beam accelerators

TT100
3 to 10 MeV
1m cavity
0.83 MeV/Pass
Beam < 40kW

TT200/T300
3 to 10 MeV
2m cavity
1.0 MeV/Pass
Beam < 190kW

TT1000
3 to 7 MeV
2m cavity
1.2 MeV/Pass
Beam < 630kW

Protect, Enhance, and Save Lives - 34 -

Options for the sterilization of medical devices

- Steam (incompatible with most polymers)
- Ethylene Oxyde
  - Inexpensive
  - EtO is explosive, toxic and harmful to the environment
  - EtO sterilization may leave harmful residues
- Irradiation
  - Cobalt
  - E-beam
  - X-ray

The options for sterilization by irradiation (1)

- **Gammas from Co60** ($T_{1/2}$=5.2 y; γ_1=1.33 MeV; γ_2=1.17 MeV)
  - Low investment cost, specially for low capacities
  - Simple and reliable, scalable from 100 kCuries to 6 MCuries (about 5 kg of Co-60)
  - Isotropic radiation > inefficiencies in use
  - Pallet irradiation, but low dose rate > slow process
  - Absolutely no activation
  - Cannot be turned OFF > inefficient if not used 24/7
  - Growing security concern: the cobalt from a sterilization plant could be used to make dirty bombs

The options for sterilization by irradiation (2)

- **Electron beams**
  - Directed radiation > Efficient use
  - Lowest cost of sterilization for large capacities
  - Can be turned OFF > safer
  - Short range (4.5 g/cm² at 10 MeV) > 2-sided irradiation of boxes
  - More complex dose mapping
  - Minimal, hardly measurable, but non zero activation

The options for sterilization by irradiation (3)

- **X-Rays from E-beams**
  - Excellent penetration
  - Simple dose mapping
  - Pallet irradiation
  - Directed radiation > Efficient use
  - Loss of a factor 10 in energy when converting e-beams to photons
  - Cost of sterilization higher than electrons
  - Cost of sterilization is generally higher by X-Rays than Cobalt if used 24/7, excepted for very large capacities
  - Can be turned OFF > safer
  - Minimal, hardly measurable, but non zero activation

Food irradiation applications

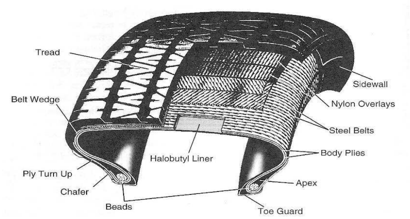
- **Low Dose Applications (< 1kGy)**
  - **Phytosanitary** Insect Disinfection for grains, papayas, mangoes, avocados...
  - **Sprouting Inhibition** for potatoes, onions, garlic...
  - **Delaying of Maturation**, parasite disinfection.

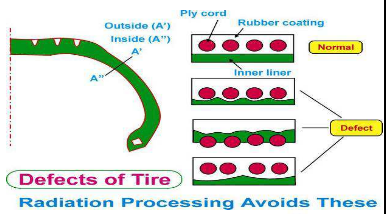
- **Medium Dose Applications (1 – 10 kGy)**
  - **Control of Foodborne Pathogens** for beef, eggs, crab-meat, oysters...
  - **Shelf-life Extension** for chicken and pork, low fat fish, strawberries, carrots, mushrooms, papayas...
  - **Spice Irradiation**

- **High Dose Applications (> 10 kGy)**
  - **Food sterilization** of meat, poultry and some seafood is typically required for hospitalized patients or astronauts.

E beam treatment of Tires

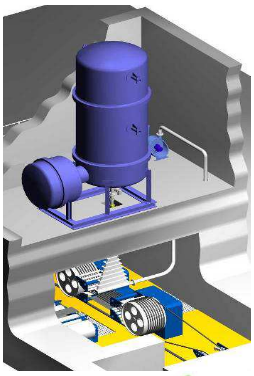
- Reduction in material hence in the weight of the tire
- Relatively low cost synthetic rubber can be used instead of costly natural rubber without a loss in strength
- The radiation pre-vulcanization of body ply is achieved by simply passing the body ply sheet under the scan horn of an electron accelerator to expose the sheet to high-energy electrons
- Higher production rates
- Construction of green tires
- Reduction of production defects





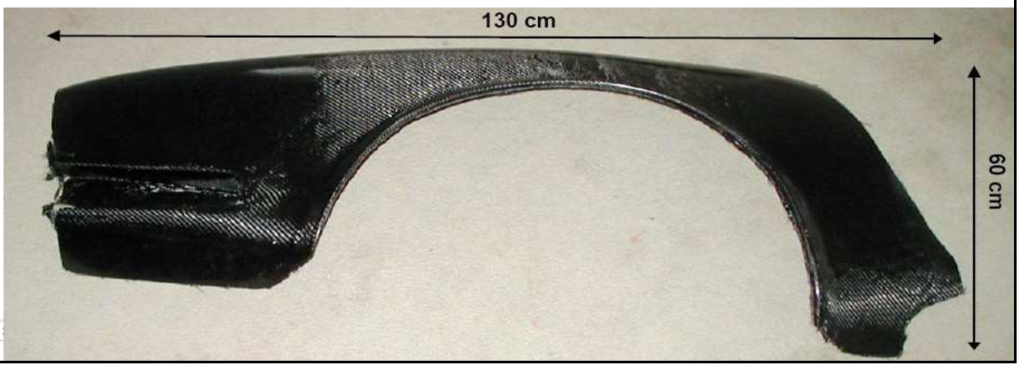
Polymer Cross-Linking

- **Wires** stand higher temperature after irradiation
- **Pipes** for central heating and plumbing
- **Heatshrink elastomers** are given a memory

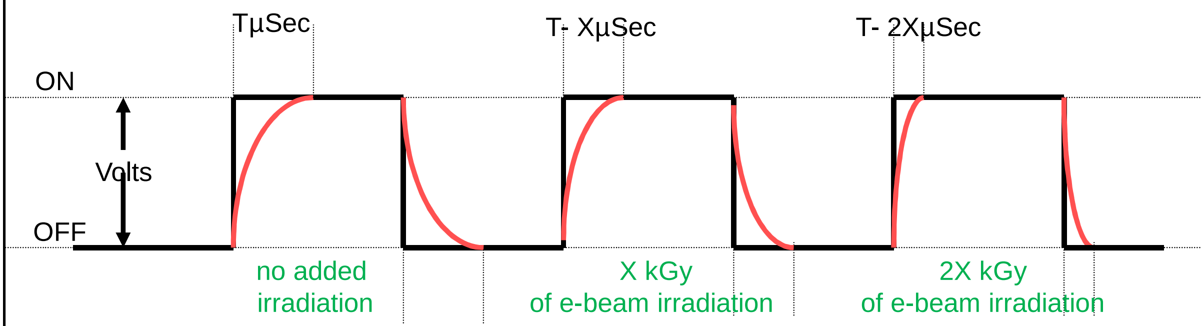


Composite curing: X-ray Cured Carbon Fiber

- Sports Car Fender made light, restistant and requiring less fuel



E-beam irradiation improves SC switching speed

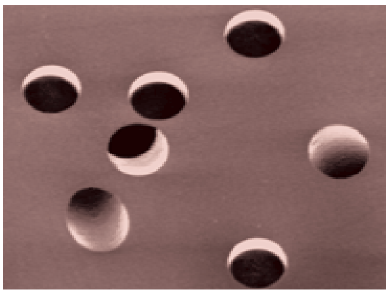


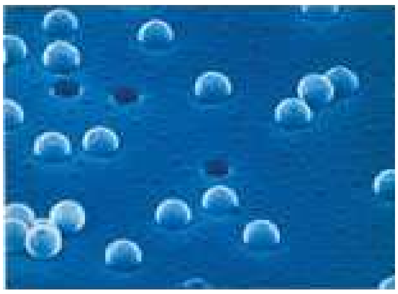
Typical semicondutors:

- fast recovery diodes
- power diodes
- Bipolar power transistors
- power MOSFETs
- power rectifiers
- IGBT's
- thyristors
- silicon-controlled rectifiers

Microfiltration membranes by heavy ions

- Heavy ion beams are used to produce track-etched microfiltration membranes, commercialized i.a. under the brand name "Cyclopore"
- In these membranes, tracks of slow, heavy ions crossing a sheet of polymer are chemically etched, giving cylindrical pores of very accurate diameter





Beam delivery options 1/3 : Rhodotron E-beam

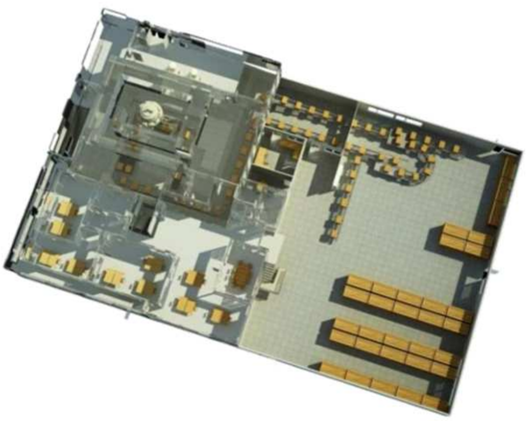
1

Rhodotron E-beam
10 MeV E-beam
Boxes

eXelis
5 or 7 MeV X-ray
Pallets

Rhodotron Duo
10 MeV E-beam
+ 5 or 7 MeV X-ray
Boxes

Rhodotron 10 MeV E-beam



http://www.iba-sterilization.com/rhodotron-e-beam-sterilization-solution

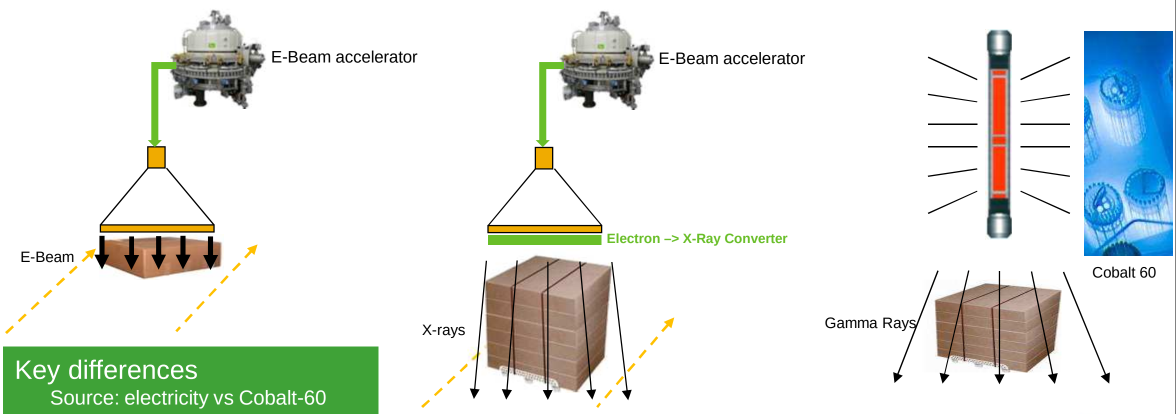
Beam delivery options 1/3 : Rhodotron E-beam

Rhodotron E-beam
10 MeV E-beam
Boxes

2
eXelis
5 or 7 MeV X-ray
Pallets

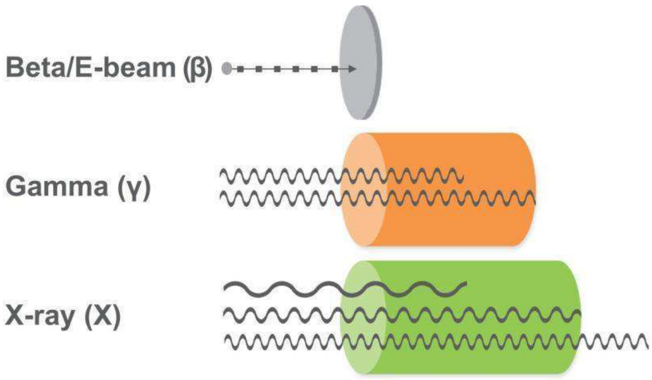
Rhodotron Duo
10 MeV E-beam
+ 5 or 7 MeV X-ray
Boxes

Irradiation Processing Comparison



Key differences
- Source: electricity vs Cobalt-60
- Directive vs Isotropic
- Switch on/off vs continous radiation

Irradiation Penetration Properties



Deeper **Penetration**

-> Bigger **Packaging**

-> Better **Quality**

Beam delivery options 1/3 : Rhodotron E-beam

Rhodotron E-beam
10 MeV E-beam
Boxes

eXelis
5 or 7 MeV X-ray
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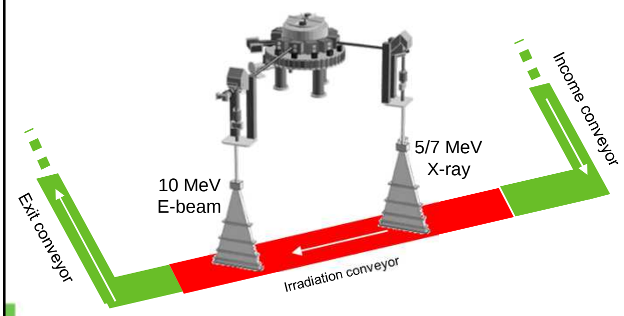
3

Rhodotron Duo
10 MeV E-beam
+ 5 or 7 MeV X-ray
Boxes

Rhodotron DUO

One irradiation, one conveyor, two technologies



- **Rhodotron DUO**
  - One accelerator
  - One conveyor
  - Two technologies
- **E-beam**
  - Beam overlapping
  - Double side
- **X-ray**
  - Product overlapping
  - Multipass processing

Rhodotron DUO – E-beam mode

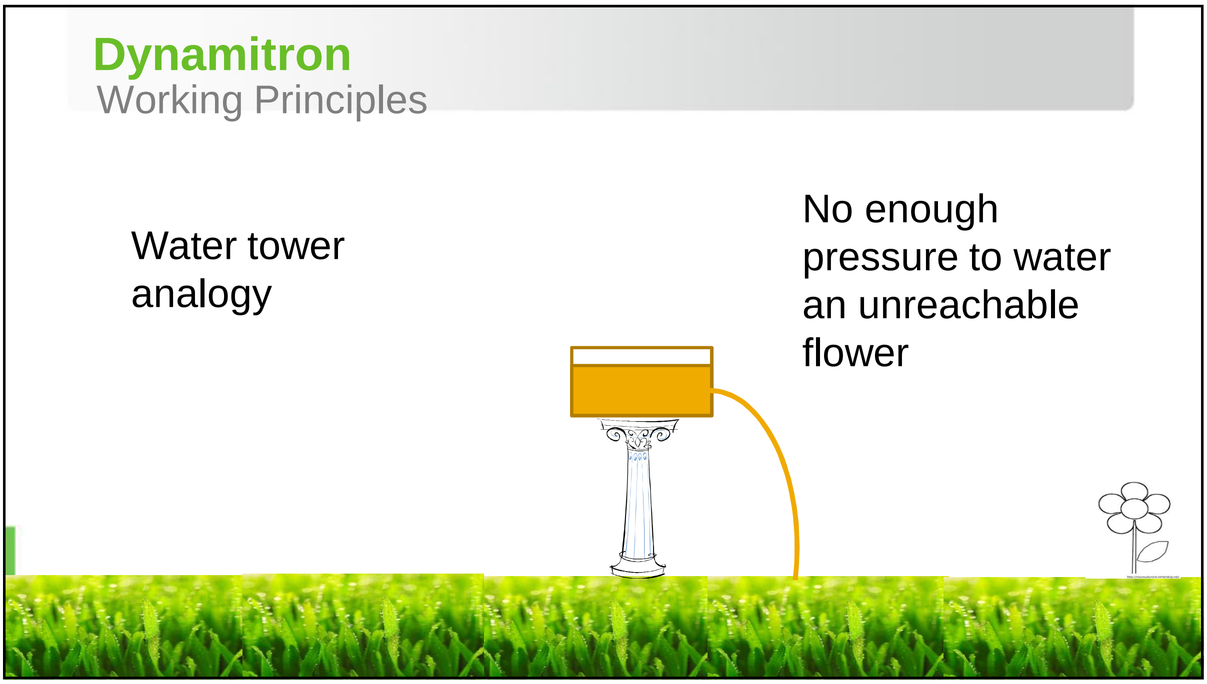
Rhodotron DUO – X-ray mode

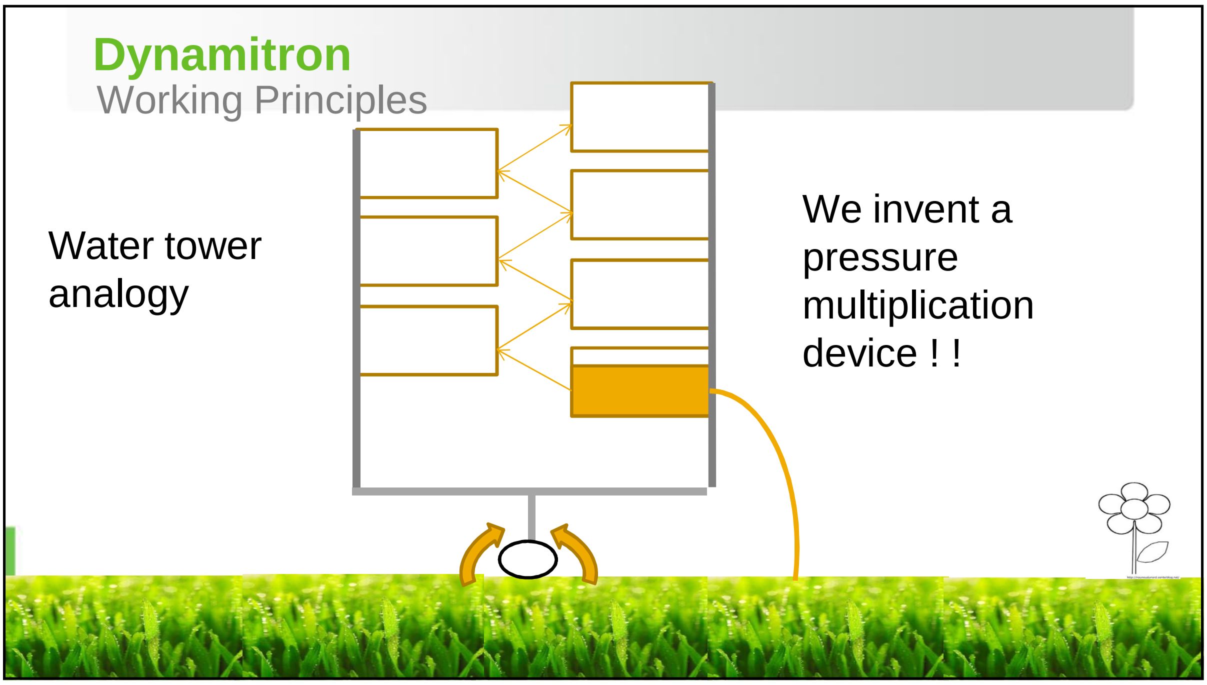
The Industrial Business needs ?

The dream machine

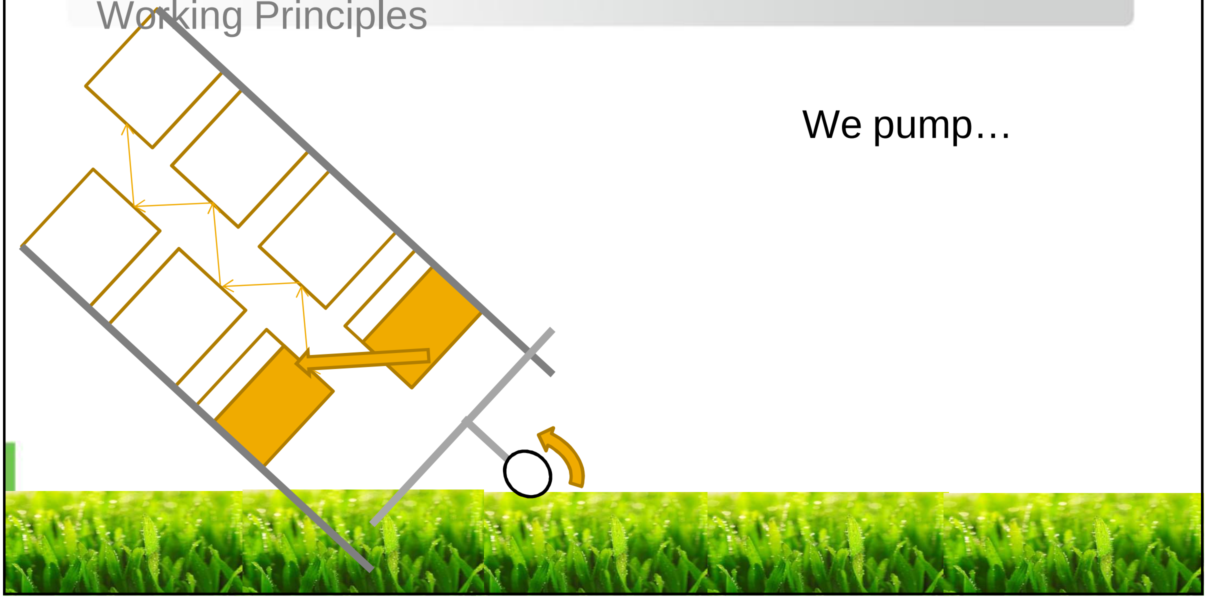
- **Electron beam accelerator with:**
  - Fixed energy between 800 keV and 10 MeV (versatility with multiple BTLs)
  - Low energy dispersion (few %)
  - Fast beam current control for accurate dose control
  - Continuous beam for scanning and higher throughput
  - High electron beam power for X-ray generation (up to 700 kW)
  - High efficiency for lower energy footprint (> 35%, Linacs < 20%)
  - High robustness, high up time, easy tuning and maintenance
  - Low cost

↳ **Perfect competitor to Linacs !**


Dynamitron
Working Principles
Water tower analogy
No enough pressure to water an unreachable flower


Dynamitron
Working Principles
Water tower analogy
We invent a pressure multiplication device ! !

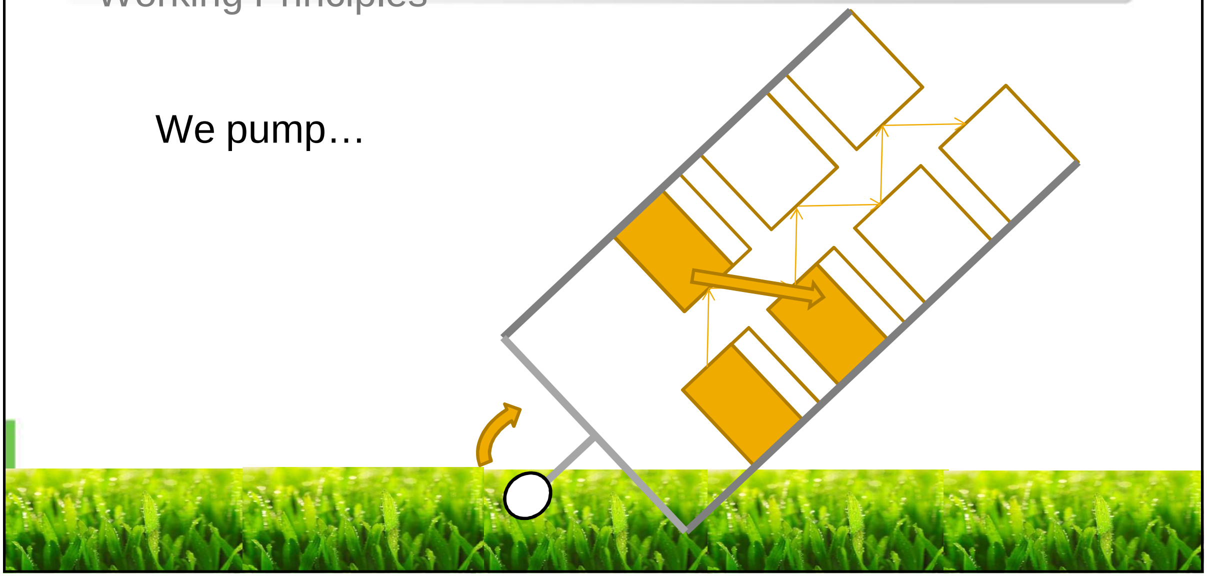
Dynamitron
Working Principles



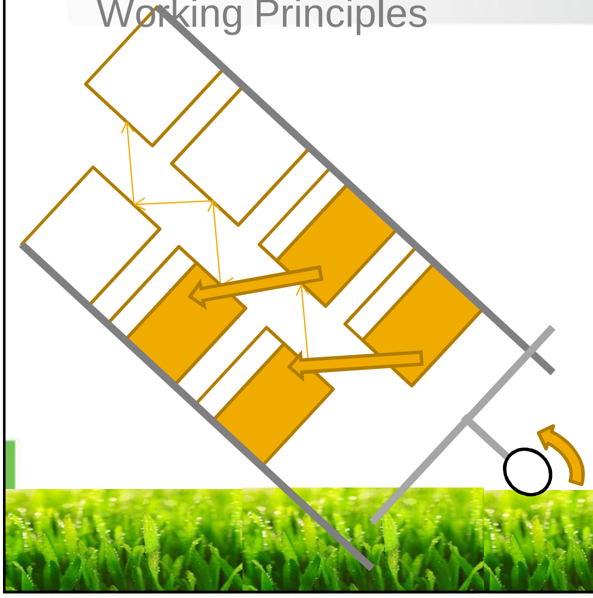
We pump…

Dynamitron
Working Principles

We pump…



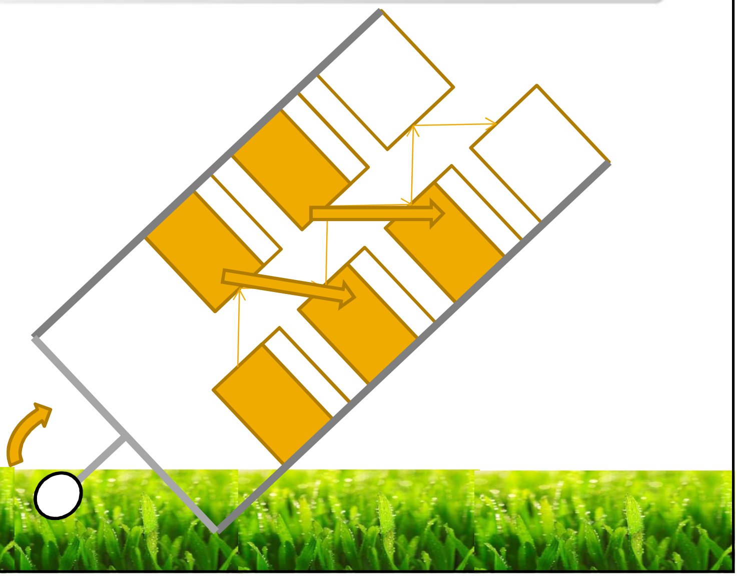
Dynamitron
Working Principles



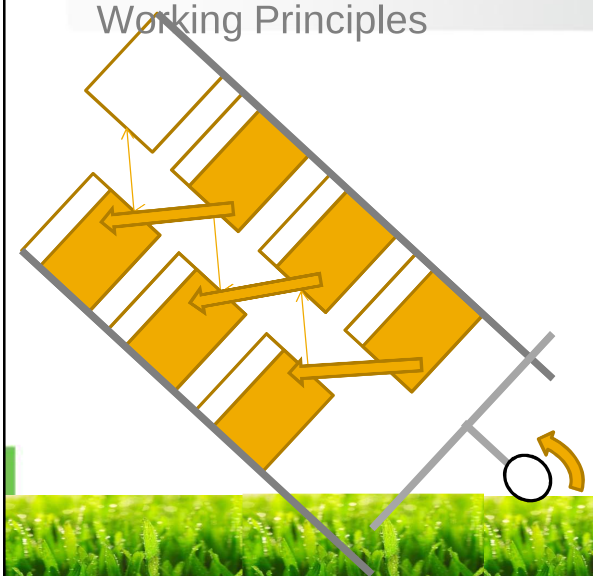
We pump…

Dynamitron
Working Principles

We pump…



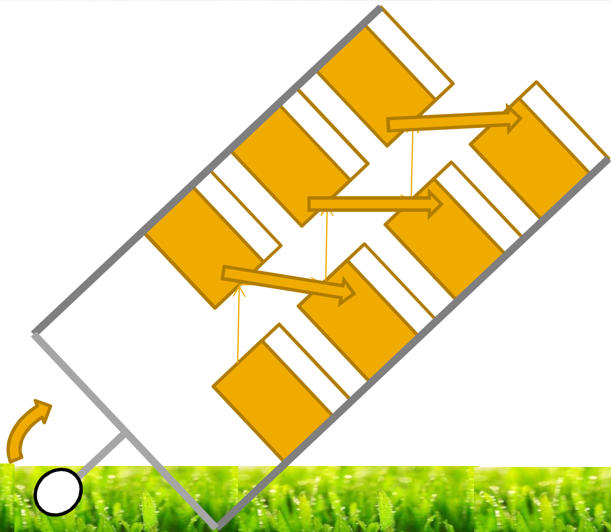
Dynamitron
Working Principles



We pump…

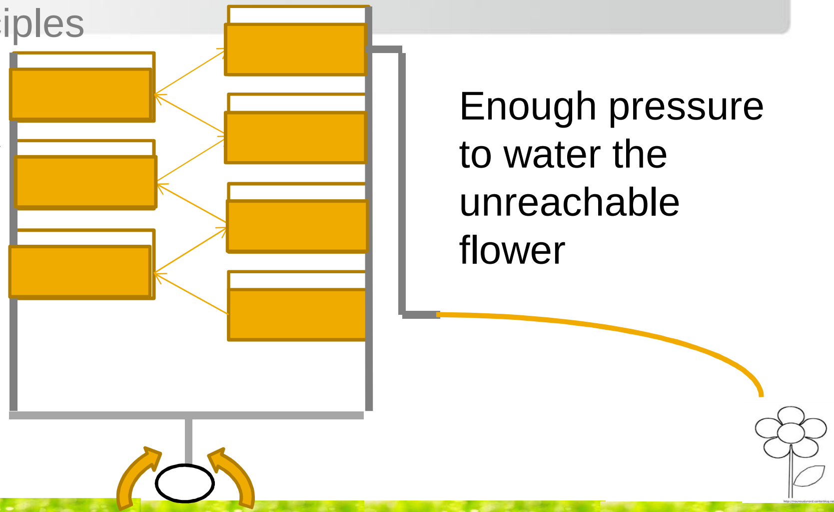
Dynamitron
Working Principles

We pump…



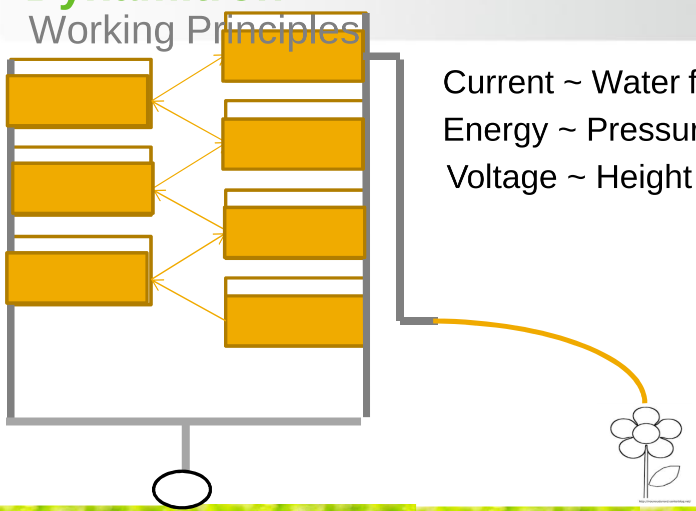
Dynamitron
Working Principles

Voltage ~ Height
Current ~ Water flow
Energy ~ Pressure

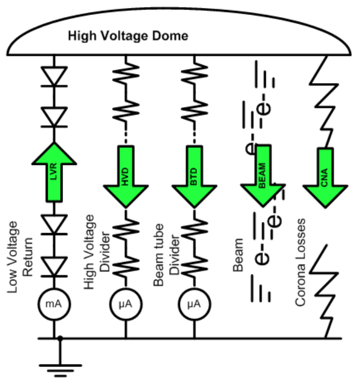


Enough pressure to water the unreachable flower

Dynamitron
Working Principles



Current ~ Water flow
Energy ~ Pressure
Voltage ~ Height



Some Dynamitron …

BGS 5 MeV



Some Dynamitron…

BGS – 5 MeV

- 5 MeV
- 50 mA
- 500 kW
- In line


Some Dynamitron projects

Yagami – How to make a protons out of a Dynamitron

1. Reverse polarity
2. Make the dome bigger
3. Replace the simple filament by a complex ion source system ☺

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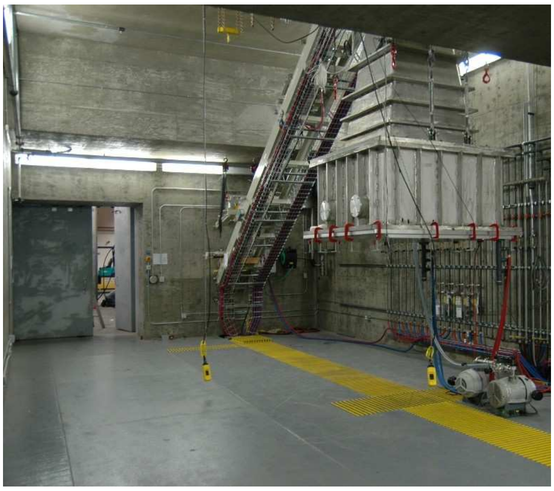
Some Dynamitron projects

Sigen



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